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PRELIMINARY REPORT ON THE FUNDAMENTALS OF THE
CONTROL OF TURBINE-PROPELLER JET POWER PLANTS

By H. Kühl

Translation

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PRELIMINARY REPORT ON THE FUNDAMENTALS OF THE CONTROL OF
TURBINE-PROPELLER JET¹ POWER PLANTS*

By H. Kühn

SUMMARY

On the basis of the investigations so far completed on the behavior of PTL¹ power plants under various operating conditions, in which the influence of the propeller characteristics is of considerable importance, the most important aspects of a control system for turbine-propeller jet power plants are deduced. A simple possible means for its concrete realization, which is also applicable to TL [NACA comment: TL, jet] power plants, is presented by means of examples. A control device of this kind is now being developed.

INTRODUCTION

The investigations of the control of turbine-propeller jet power plants, which were carried out following the previous work (references 1 to 3) on the control of gas-turbine power plants for aircraft, are not yet completed; however, the results now available allow the essential outlines of a simple and adequate control system for turbine-propeller jet power plants to be shown. Because regulators for turbine-propeller jet power plants will be needed in the immediate future, this report will give the most practically important results obtained at the present stage of the investigations.

Whereas in the jet power plant there is, aside from the fuel supply, only one adjustable part, namely, the jet nozzle, to be controlled, in the turbine-propeller jet power plant there are in

*"Vorläufiger Bericht über die Grundlagen der Regelung von PTL-Triebwerken." Deutsche Luftfahrtforschung, Untersuchungen und Mitteilungen Nr. 1272. Deutsche Versuchsanstalt f. Luftfahrt, E. V., Inst. f. motorisches Arbeitsverfahren und Thermodynamik, Berlin-Adlershof, ZWB, June 9, 1944.

¹ NACA comment: turbine-propeller jet, PTL.

the first instance two such adjustable parts, the propeller and the jet nozzle. Only on the basis of experimental findings is it possible to answer the question of whether the alteration of the jet-nozzle cross section may be dispensed with in general or in particular cases. Insofar as the setting of the jet nozzle and of the variable-pitch propeller is not fixed, there is added to the three arbitrarily variable parameters associated with the jet power plant the Mach number Ma_0 of the flight speed w_0 ($Ma_0 = w_0 / \sqrt{g\kappa_L R_L T_0}$; $\sqrt{g\kappa_L R_L T_0}$ = the velocity of sound in the atmosphere), the pressure ratio in the compressor p_2/p_1 , and the ratio of the temperature ahead of the turbine to that of the atmosphere T_3/T_0 , a fourth arbitrarily variable parameter, that is, the division of power output between jet nozzle and propeller.

I. INVESTIGATION OF TURBINE-PROPELLER JET POWER PLANT

IN OPTIMUM DIVISION OF PROPULSIVE

POWER BETWEEN JET NOZZLE

AND PROPELLER

For simplification of the very complicated relations involved here, it is appropriate to consider first turbine-propeller jet power plants having that division of power output at which the specific fuel consumption reaches its optimum value². For this case it may easily be shown³ that the following equation applies to the velocity w_5 of the gas emerging from the jet nozzle:

$$w_5 = \frac{\varphi_d^2}{\eta_{\delta p} \eta_{\delta t-pol}^*} w_0$$

²Insofar as the gas flow through the turbine is unaffected by the alteration of back pressure, the greatest thrust is also attained at this same division of power output.

³See appendix for the derivation.

or

$$w_5 = \frac{\varphi_d^2}{\left(\frac{d S_p}{d N_{p-w}}\right)_{\lambda, n = \text{constant}} \eta^*_{\delta t - \text{pol}}} = \frac{\varphi_d^2}{\left(\frac{d k_s}{d k_l}\right)_{\lambda = \text{constant}} \eta^*_{\delta t - \text{pol}}} u_p$$

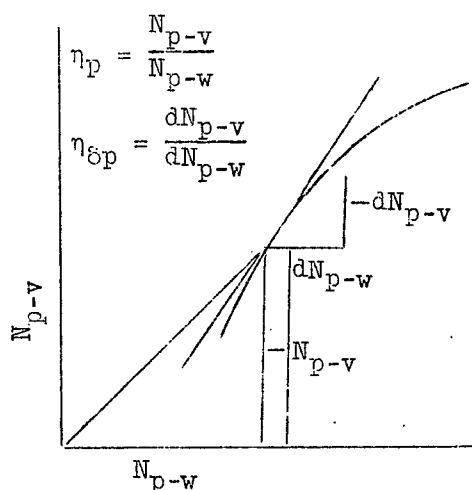
where

φ_d velocity coefficient of jet nozzle

$$\eta_{\delta p} = \left(\frac{d N_{p-v}}{d N_{p-w}}\right)_{\lambda, n = \text{constant}} = \lambda \left(\frac{d k_s}{d k_l}\right)_{\lambda = \text{constant}}$$

$$= \eta_p + \left[\frac{d \eta_p}{d (\ln N_{p-w})}\right]_{\lambda, n = \text{constant}} = \eta_p + \left[\frac{d \eta_p}{d (\ln k_l)}\right]_{\lambda = \text{constant}}$$

which is the "differential efficiency" of the propeller, that is, the efficiency with which a change in the shaft power input to the propeller is utilized. (See sketch.)



$$\eta_{\delta t-pol}^* = \left(\frac{d L_t}{d L_{t-pol}^*} \right)_{n = \text{constant}} = \eta_{t-pol}^* + \left[\frac{d \eta_{t-pol}^*}{d (\ln L_{t-pol}^*)} \right]_{n = \text{constant}}$$

which is the differential efficiency of the turbine calculated from the polytropic curve⁴ and from the total (static and dynamic) pressure ahead of and behind the turbine analogous to $\eta_{\delta p}$.

S_p propeller thrust

N_{p-w} shaft power input to propeller (mkg/sec not hp)

$\lambda = \frac{w_o}{u_p}$ advance ratio of propeller

n speed, rpm

u_p tip speed of propeller

$k_s = \frac{S_p}{\frac{\rho}{2} u_p^2 \frac{D_p^2 \pi}{4}}$ thrust coefficient of propeller

$k_l = \frac{N_{p-w}}{\frac{\rho}{2} u_p^3 \frac{D_p^2 \pi}{4}}$ power coefficient (= turning moment coefficient k_d) of propeller

$N_{p-v} = S_p w_o$ propulsive power output of propeller (mkg/sec not hp)

$\eta_p = \frac{N_{p-v}}{N_{p-w}} = \lambda \frac{k_s}{k_l}$ efficiency of propeller

ρ air density

⁴By use of the polytropic curve any special consideration of the recoverable heat of friction may be disregarded.

D_p diameter of propeller

$\eta^*_{t-pol} = \frac{L_t}{L^*_{t-pol}}$ turbine efficiency calculated from polytropic curve and from total pressure ahead of and behind turbine

L_t turbine power output per kilogram of gas

L^*_{t-pol} polytropic work of expansion in turbine between total pressures ahead of and behind turbine per kilogram of gas

If η_p or η^*_{t-pol} is constant

$$\eta_{\delta p} = \eta_p$$

or

$$\eta^*_{\delta t-pol} = \eta^*_{t-pol}$$

In order to obtain an over-all view of the relations in the turbine-propeller jet power plant, in a manner similar to that used earlier (reference 3) for the jet power plant, the behavior of the power plant will be investigated at various values of Mach number Ma_0 , flight speed, pressure ratio in the compressor p_2/p_1 , and temperature ratio T_3/T_0 when operating with optimum division of power output, that is, with the jet velocity determined as in the previous equation and with constant efficiencies of the component units. The following values are assumed as the basis of the computations:

Turbine efficiency calculated on polytropic curve	$\eta^*_{t-pol} = 0.75$
Compressor efficiency calculated on polytropic curve	$\eta_{l-pol} = 0.85$
Efficiency of propeller and gearing	$\eta_p = 0.75$
Efficiency of impact scoop	$\eta_{st} = 0.90$
Efficiency of combustion chamber	$\eta_b = 0.95$
Velocity coefficient of jet nozzle	$\varphi_d = 0.96$
Outflow coefficient of turbine nozzle	$\mu_t = 0.94$
Pressure drop $p_2 - p_3$ in combustion chamber disregarded	$p_3 = p_2$

Figure 1 shows⁵ an end result that is particularly important for regulation, namely the temperature ratios T_3/T_0 , and T_3/T_1 (T_1 , temperature ahead of the compressor) at which the specific fuel consumption b_S for a particular jet thrust attains its optimum value b_{Smin} . Additional curves show the temperature ratios at which the specific fuel consumption is 2 and 5 percent greater than the minimum. In the region lying between two curves of the same family [NACA comment: Apparently families of constant deviation] the difference from the optimum value of the specific fuel consumption remains in each case less than the respective 2 or 5 percent value.

The shape of these curves is without doubt very strongly influenced by the assumptions that are the basis of the computations; in particular, the changes in the component efficiencies, which occur in actual practice in different operating regions, may be expected to cause considerable differences from the shape computed here. However, because with the exception of the propeller efficiency the curves of the component efficiencies plotted against various flight speeds will with appropriate design of the power plant be approximately the same in each case, the following conclusions for which general validity may probably be claimed can be drawn from figure 1 independently of specific values:

1. The influence of flight speed on the combinations of values of T_3/T_0 or T_3/T_1 and of p_2/p_1 that are most favorable with regard to fuel consumption is very limited, and therefore it may be disregarded even when a high standard of accuracy of control is required, provided that no considerable changes occur in the propeller efficiency. (See following paragraphs.)

2. There is only a small variation of b_S/b_{Smin} over a rather large region [NACA comment: For a rather large variation of temperature ratio at constant pressure ratio]; an exact adherence to the most favorable values of T_3/T_0 or T_3/T_1 is thus unnecessary.

In figure 2 the jet-nozzle flow area F_d (expressed in terms of its ratio to the turbine-nozzle flow area F_t) is shown as a function of the thrust coefficient $\sigma = S/F_t p_0$ (total thrust per unit of turbine-nozzle flow area at an atmospheric pressure of 1),

⁵The differences between the curves within each group are less than the limits of accuracy of the computations at the present time.

for two Mach numbers of flight speed. Most strikingly evident is the marked increase of the jet-nozzle flow area with increasing thrust coefficient as well as an increase of jet-nozzle flow area with decreasing flight speed, which follows from the proportion of jet velocity to flight speed. At full power output it would, according to this reasoning, be necessary, in order to realize the most favorable division of output between jet and propeller, to increase the jet-nozzle flow area with decreasing speed. Considerations to be set forth later will show, however, that because of the change in propeller efficiency, which was disregarded in the computations, such a regulation is, in general, unnecessary and useless.

By observing the most important practical flying condition in practice, that of horizontal flight, it may easily be seen that the following relation applies for a particular aircraft with a coefficient of resistance c_w :

$$\sigma \approx c_w Ma_o^2$$

The influence of the thrust coefficient on decreasing jet-nozzle flow area with decreasing flight speed largely balances the direct influence of flight speed, and therefore differences in the jet-nozzle flow area that are calculated to meet the requirement of optimum division of power output at various loadings are not so very large.

II. INFLUENCE OF DIVISION OF POWER OUTPUT ON

BEHAVIOR OF TURBINE-PROPELLER JET POWER PLANT

An investigation will now be made of the extent of the decrease in power output and fuel consumption if the most favorable division of power output is departed from. Figure 3 shows, for $Ma_o = 0.3$ and 0.7 in addition to the $b_g = b_{Smin}$ curve taken from figure 2, the curve of those jet-nozzle flow areas for which, with the same correlation between T_3/T_o and p_2/p_1 [NACA comment: The correlation as for b_{Smin} in optimum division of output] the specific fuel consumption is increased 2 percent above the optimum value and the thrust is decreased 2 percent⁶. It is evident that

⁶Because with decreasing thrust b_{Smin} also increases, the distance between the curves $b_g = 1.02 b_{Smin}$ is somewhat greater than the distance between the curves $\sigma = 0.98 \sigma_{max}$.

the area between two associated curves, in which the deterioration of the specific fuel consumption and of the thrust remains less than 2 percent, is very large, particularly for $Ma_0 = 0.3$. Although the numerical values must not be generalized, this general truth follows rather certainly from these investigations:

The change in the specific fuel consumption and in the total thrust due to a change in the jet-nozzle flow area over a rather large range is so small that rather considerable departures from the theoretical optimum value of the jet-nozzle flow area are permissible.

In accordance with the previous paragraph, during horizontal flight an exact adaptation of the jet-nozzle flow area to the operating conditions from moment to moment would offer no important advantage with regard to fuel consumption as compared with a fixed jet-nozzle flow area, therefore the question arises of whether regulation of the jet-nozzle flow area can be dispensed with entirely. In order to answer this question decisively, consideration of the actual course of variation of the propeller efficiency is necessary.

III. CONSIDERATION OF VARYING EFFICIENCY OF PROPELLER

The simplifying assumption upon which the foregoing reasoning has been based, namely that the propeller efficiency remains constant, departs rather markedly from the actual situation over a large part of the propeller-characteristics diagram. If the difference between computation and reality is not to become too large, an effort must be made to avoid as far as possible those parts of the propeller-characteristics diagram that exhibit marked decreases in efficiency. In so doing a certain approximation of the results will be determined that would be obtained if computations, which took into account the varying efficiencies (see the equation of w_5 with $\eta_{\delta p}$), were made for a specific power plant; in such a computation the requirement of optimum fuel utilization and maximum total thrust would necessarily lead to the avoidance of most of the region of poor propeller efficiencies.

The following fact is decisive for the behavior of the propeller: The lift coefficient, which is operative on the blades of a particular variable-pitch propeller at a particular speed, air density, and power is many times greater at low flight speeds than at high speeds, especially in propellers with very high advance ratios, such as the propellers being considered must have because of the high flight speeds involved. Hence, at low speeds and especially at take-off,

the danger arises of a separation of the flow and a consequent limitation of the propeller thrust, whereas at high flight speeds the propeller efficiency drops markedly because of the small lift coefficients in conjunction with high tip-speed Mach numbers. As an example, figure 4 shows a propeller-characteristics diagram recorded by the DVL⁷ (reference 4) (Mach number less than 0.3).

In order to bring out in its most generally valid form the relation between the operating conditions of the turbine-propeller jet power plant and the location of the operating point in the propeller-characteristics diagram, the following representation will be found appropriate. From

$$H_{l-ad} = \psi \frac{u_l^2}{2g}$$

it follows that the tip speed of the propeller is

$$u_p = v_{pl} \sqrt{\frac{2g H_{l-ad}}{\psi_n}} \sqrt{\frac{\psi_n}{\psi}}$$

Also

$$w_o = Ma_o \sqrt{g \kappa_{LL} R T_o}$$

where

H_{l-ad}	adiabatic pressure head of compressor
ψ	pressure coefficient of compressor
ψ_n	pressure coefficient of compressor for a chosen reference point, which may be design point
u_l	tip speed of compressor
g	acceleration of gravity

⁷The efficiency, the values of which are used in this figure, is not precisely identical with η_p .

$v_{p\lambda} = \frac{u_p}{u_\lambda}$ ratio of tip speed of propeller to that of compressor

R_L gas constant for air

κ_L exponent of adiabatic curve for air

By consolidation of the factors that are unvarying for a particular power plant into constants C_1 , C_2 , and C_3 , the following equations for the characteristics of the propeller may be derived from previous equations:

$$\text{Advance ratio } \lambda = C_1 \frac{Ma_0}{\sqrt{\frac{H_{\lambda-\text{ad}}}{R_L T_0}}} \sqrt{\frac{\psi}{\psi_n}}$$

$$\text{Thrust factor } k_s = C_2 \frac{\sigma_p}{\frac{H_{\lambda-\text{ad}}}{R_L T_0}} \frac{\psi}{\psi_n}$$

$$\text{Power factor } k_\lambda = C_3 \frac{\Lambda}{\left(\frac{H_{\lambda-\text{ad}}}{R_L T_0}\right)^{\frac{3}{2}}} \left(\frac{\psi}{\psi_n}\right)^{\frac{3}{2}}$$

in which the portion of the thrust coefficient of the power plant attributable to the propeller is

$$\frac{S_p}{F_{tp_0}} = \sigma_p$$

and the characteristic value for the power transmitted to the propeller is

$$\frac{N_{p-w}}{F_{tp_0} \sqrt{g \kappa_L R_L T_0}} = \frac{\sigma_p Ma_0}{\eta_p} = \Lambda$$

Thus if the quantity

$$\bar{k}_l = \frac{\Lambda}{\left(\frac{H_{l-ad}}{R_L T_0}\right)^{\frac{3}{2}}}$$

or

$$\bar{k}_s = \frac{\sigma_p}{\frac{H_{l-ad}}{R_L T_0}}$$

is plotted against the quantity

$$\bar{\lambda} = \frac{Ma_0}{\frac{H_{l-ad}}{R_L T_0}},$$

a graph is obtained that differs from propeller-characteristics diagrams of the type shown in figure 4 only in the scale of the coordinates and the influence of the correction factor ψ/ψ_n .⁸ But the ratio ψ/ψ_n , which is a function of the compressor-characteristics diagram, changes only to a limited degree in the region of higher power-plant output (relative to the respective full power at any moment). It decreases with decreasing gas temperature and especially with decreasing speed and thereby causes a shift of the operating point along a parabola of the third or of the second degree passing through the zero point of the coordinate system.

Figure 5 shows this conformation for the idealized example ($Ma_0 = 0.3$ and 0.7) already considered. The curves of constant pressure ratio are here straight lines parallel to the ordinate axis. The value of \bar{k}_l rises primarily with increasing temperature ratio T_3/T_0 . The variation of \bar{k}_l with Mach number Ma_0 is different in various

⁸For a particular power plant, it will naturally be preferable to make use of the direct relation between H_{l-ad} and n (in order that the correction factor ψ/ψ_n disappears) and to use $n/\sqrt{T_1}$ as parameter instead of p_2/p_1 .

parts of the operating range. At the values principally in current use, this variation is quite small for the case discussed here (namely, that of most advantageous division of propulsive power between propeller and jet nozzle at constant efficiencies of the component units). With a fixed jet-nozzle flow area there would be, with customary design, a decrease of k_7 of the order of magnitude of 10 to 30 percent with a decrease in Mach number Ma_0 from 0.7 to 0.3.

From figure 4 it is evident that with, for example, an advance ratio $\lambda = 0.12$ (corresponding to a flight speed of 100 km/hr, if the flight speed for $\lambda = 1.0$ amounts to about 800 km/hr) a limit is already reached at a blade angle of incidence of 31.5° and a consequent power factor of $k_7 = 0.02$ beyond which a further increase of power applied to the propeller will produce no increase of the propeller thrust.⁹ If it is required that this limit not be exceeded and if, for example, at sea level the ratio of propeller power input at low flight speed to that at maximum speed is 0.8 to 1, then accordingly at maximum speed at sea level (for example, $\lambda = 0.8$) a power factor of not more than $k_7 = 0.025$ would be possible, whereas the optimum propeller efficiency would lie at greater values of k_7 . With decreasing atmospheric temperature, that is, increasing altitude, at unaltered speed and combustion temperature T_3 in horizontal flight k_7 will increase and also flight speed and λ in accordance with the marked increase of σ .

Accordingly, at full power an increase of the value k_7 at high flight speeds and a decrease at low flight speeds must be found; this is possible in the first case by means of an increase and in the second by means of a decrease of the jet-nozzle flow area as compared with that computed for a constant propeller efficiency. Therefore the considerable increase in the most advantageous jet-nozzle flow area calculated for decreasing flight speed at high thrust coefficients with a constant propeller efficiency is substantially reduced and under certain circumstances even more than balanced.

More exact results will be obtained if the equation for the most advantageous jet velocity w_5 is used with the actual differential efficiency of the propeller $\eta_{\delta p}$. This efficiency would be, for example in figure 4, at $\lambda = 0.8$ and $k_7 = 0.025$ about 15 percent larger (that is, $\eta_{\delta p} - \eta_p = 0.15$) and at $\lambda = 0.43$ and

⁹Because $\eta_{\delta p} = 0$ at this point, the maximum propulsive effect would lie at a still smaller propeller power.

$k_1 = 0.022$ about 10 percent smaller than the propeller efficiency proper. Whereas the jet-nozzle flow area for most advantageous division of power, as computed for constant efficiencies of the component units would be about 1.7 times as large for $\lambda = 0.43$ as for $\lambda = 0.8$ if the value of η_{sp} is used instead of η_p , the difference in most advantageous jet-nozzle flow areas will amount to only about 20 percent. In this case an exact regulation of the jet-nozzle flow area would provide no noteworthy advantage over a properly selected fixed jet-nozzle flow area.

Conversely, at still lower flight speeds with full power, particularly in take-off, a reduction of the jet-nozzle flow area as compared with the value for high-speed flight would lead to an increase of the thrust, which, under certain circumstances, could be significant. It is planned to investigate these questions further. Possibly greater differences will appear with various power plants, depending upon the respective designs.

By further consideration of the especially important case of horizontal flight, using the already noted relation $\sigma \approx c_w Ma_0^2$, it is possible to obtain from figure 5 an approximate survey of the position of the operating point in the propeller-characteristics diagram under various operating conditions. It may be seen that with decreasing power, $\bar{\lambda}$ generally decreases only to a limited degree at first, because — excepting at very high altitudes — c_w changes only slightly in the region of high power (relative to full power) and therefore the influence of Ma_0 on $\bar{\lambda}$ is to a large extent balanced by the opposite influence of the thrust coefficient σ , which decreases roughly with Ma_0^2 . Not until the flight conditions approach those of flight at the best gliding angle does there result, corresponding to the marked increase of c_w occurring then, a rather marked reduction of $\bar{\lambda}$. The values of the actual advance ratio and of the actual power factor k_1 are less than the values $\bar{\lambda}$ and \bar{k}_1 by the factors $\sqrt{\psi/\psi_n}$ or $(\psi/\psi_n)^{3/2}$, respectively.

It is evident from these considerations that a correlation of T_3/T_0 or T_3/T_1 with p_2/p_1 as illustrated in figure 1 (curve $b_S = b_{Smin}$ in fig. 5) if computed on the assumption of constant propeller efficiency would be rather disadvantageous because with decreasing power the value of \bar{k}_1 drops relatively rapidly here and a region of poor propeller efficiency would thus be entered. The most advantageous values of T_3/T_1 as a function of p_2/p_1 lie substantially higher when the actual propeller efficiency is

taken into consideration. This is also shown by the relatively steep course of the curves $\sigma = \text{constant}$ in figure 5, which is very much steeper than the slope of the curves of constant propeller efficiency in the propeller-characteristics diagram. Hence, in this region where the values of \bar{k}_1 are smaller than correspond to maximum propeller efficiency, at a given thrust coefficient the propeller efficiency increases with increasing \bar{k}_1 , that is, with increasing T_3/T_0 . Therefore, starting from full-power operation it will generally be desirable at high atmospheric temperatures, that is at low values of T_3/T_0 , to bring about a decrease of power at first primarily through a reduction of the pressure ratio p_2/p_1 , that is, of the speed with only a small decrease in the gas temperature.¹⁰ Whether this decrease also applies to low atmospheric temperatures depends upon the special characteristics of the power plant in question.

The relations are different in climbing flight. In this case, the most rapid possible reduction of \bar{k}_1 , that is starting from full-power operation the most rapid possible reduction of the gas temperature, is desirable for propeller efficiency. At lower power (relative to full power) transition could then be made back to the correlation of T_3/T_1 with p_2/p_1 selected for horizontal flight. The question of whether the gain thus obtainable justifies the required expense must be answered primarily in terms of individual cases.

An adjustment of the jet nozzle may also become necessary from the viewpoint of the loading on the propeller gear system. For the reduction of the space and weight requirements it is appropriate to design the gearing for a somewhat higher altitude than sea level. In order to avoid an overloading of the gearing at high power output at low altitudes, the jet-nozzle flow area must be so reduced after the permissible load on the gearing is reached that this loading is not exceeded; in the rest of the operating range the jet-nozzle flow area can remain fixed. In general, in the region where adjustment is necessary the jet-nozzle flow area will become smaller as the power relative to full power is greater, as the atmospheric pressure and the flight speed are higher, and as the atmospheric temperature is lower.

¹⁰Such a regulation is also advantageous with respect to the influence of Mach number on propeller efficiency (which is not expressed in fig. 4).

IV. POSSIBLE MEANS OF EFFECTING CONTROL OF TURBINE-PROPELLER JET POWER PLANT

In the control of the turbine-propeller jet power plant, arrangements for the measurement and the limitation of the fuel quantity that can operate on principles previously treated (reference 2)¹¹ will be necessary. The arrangements for the limitation of the fuel quantity are based upon the fact that, at a constant combustion-chamber efficiency, the quotient B/p_3 or the weight of fuel consumed per hour divided by the pressure ahead of the turbine, at which the maximum permissible gas temperature ahead of the turbine or the pump limit is reached, is a function of the temperature ahead of (or behind) the compressor and of the speed. As long as the velocity in the nozzles of the turbine remains below the critical velocity, a certain variation with the pressure ratio in the turbine nozzle also exists and hence with the pressure ratio p_3/p_4 in the turbine; this variation, however, insofar as it is not accounted for indirectly in the speed, may in most cases be disregarded. Marked alterations in the jet-nozzle flow area, however, might raise the question of arranging a response to this factor; this can be done in a simple manner, for example, by a small correction to p_3 dependent upon the back pressure¹² p_4 . (See subsequent paragraphs.) Changes in the combustion-chamber efficiency with changes in p_3 may also be accounted for by small corrections to p_3 .

The second function of the control system is the setting of the adjustable propeller, which may occur in the usual manner through selection of the speed. As previously shown, in the region of rather low power (relative to full power) the pressure ratio p_2/p_1 and therefore the value of $n/\sqrt{T_1}$ that corresponds to the best fuel consumption can be expressed with sufficient accuracy as a function of T_3/T_1 . For the indirect determination of the temperature ratio T_3/T_1 , use of the quotient of the weight of fuel consumed per hour divided by a pressure is appropriate. From the flow equation for the turbine nozzle it follows that

¹¹The sample designs sketched therein to illustrate the various basic principles separately from each other will naturally undergo superficial alterations in being consolidated into a single regulator unit.

¹²In many cases the following alternative would be possible: with decreased jet-nozzle flow area, a small overflow valve in the line to the injection nozzles could open and divert some of the fuel.

$$\frac{B}{p_3} = \frac{B}{G_L} \frac{F_t \chi}{(1+m) \sqrt{R_G T_3}} = \frac{m}{\sqrt{T_3}} \frac{F_t \chi}{(1+m) \sqrt{R_G}}$$

where the second factor is only slightly variable. (G_L = weight of air per unit time; χ = outflow factor, which at lower than critical pressure ratio in the turbine nozzle is a function of this ratio; (reference 1, p. 5). The fuel-air mixture ratio m with constant combustion-chamber efficiency depends only on the temperature behind the compressor T_2 and the temperature ahead of the turbine T_3 . Similarly to the fuel quantity limitation, therefore in a particular power plant with a prescribed correlation of T_3/T_1 with p_2/p_1 or $n/\sqrt{T_1}$, the quantity B/p_3 is very nearly a function of the speed n and of the temperature ahead of the compressor T_1 or conversely, n is a function of B/p_3 and T_1 . The course of this function is to be determined for each power plant in accordance with the requirement of best possible fuel utilization by use of the specific data for the component units.

In practice, however, cases can arise in which B/p_3 plotted against n exhibits a minimum or changes only so very slowly with changes in n that a sufficiently exact correlation of n with B/p_3 is either impossible or very difficult. In many cases (see fig. 6) the quantity B/p_3 is therefore of no further value for regulation because if the power were to be changed by the selection of a different value of B/p_3 the fuel quantity would only slowly reach its final value, corresponding to the change p_3 with the speed; thus the desired power changes (acceleration and deceleration) would occur too slowly.

These disadvantages are avoided if for regulation, instead of B/p_3 , the quantity

$$\frac{B}{p_1} = \frac{B}{p_3} \frac{p_2}{p_1} \frac{p_3}{p_2}$$

is used for regulation. This quantity differs from B/p_3 principally in the factor p_2/p_1 . As is evident from a previous presentation of the compressor-characteristics diagram (reference 1), for a particular power plant p_2/p_1 is a function of $n/\sqrt{T_1}$ and T_3/T_1 and also of the pressure ratio in the turbine nozzles as long as the critical pressure ratio is not reached.

Because the regulator should correlate T_3/T_1 and $n/\sqrt{T_1}$ and the influence of the pressure ratio in the turbine nozzle can also be reflected in rough approximation by consideration of its variation with $n/\sqrt{T_1}$, p_2/p_1 closely approximates a function of $n/\sqrt{T_1}$. The same conditions apply to the factor p_3/p_2 . In the case of regulation according to the criterion of optimum fuel consumption, the quantity B/p_1 can therefore also be represented as a function of n and T_1 . By means of small corrections to p_1 or p_3 , it is possible to make the approximation still better, as in the case of limitation of fuel quantity previously discussed.

In the region of higher power (relative to full power) the function $B/p_1 = f(T_1, n)$ (or the corresponding function of B/p_3) is to be so chosen that while keeping within the permissible limits for speed and gas temperature the most advantageous fuel utilization possible is achieved and at full power both the maximum permissible gas temperature ahead of the turbine and the maximum speed are reached. In general, a course of regulator action independent of the flight speed will suffice here; the course is to be determined from the specific data of the power plant in question.

As was previously shown, in the region of heavy loading results somewhat better could be secured if, starting from full-power operation, with decreasing power at high flight speeds primarily the speed is reduced but at low flight speeds primarily the gas temperature. This function could be accounted for in a simple manner by allowing the blade setting of the propeller to affect the selected speed in such a manner that in the region of low blade angles of incidence the selected speed is increased with decreasing angle of incidence, but not to exceed the maximum speed (fig. 6).

If it is necessary to have an automatic adjustment of the jet-nozzle flow area rather than using, for example, manual adjustment during take-off, the previously discussed reduction of the jet-nozzle flow area for high power at low flight speeds, especially for take-off, may be effected by a control that is a function of the pressure ratio¹³ $p_3/(p_1 - p_0)$ or of $(p_3 - p_0)/(p_1 - p_0)$. In this control a high degree of precision is unnecessary.

¹³Instead of $p_1 - p_0$, the total pressure corresponding to the flight speed may, of course, be used.

If the propeller power must be limited for the protection of the gearing, this regulation may so occur as a function of the fuel quantity that when a certain fuel quantity, corresponding in effect to the maximum permissible gear loading, is reached with further increase in the fuel quantity, the jet-nozzle flow area is reduced. An exact investigation of this regulation was not actually undertaken but it seems probable nevertheless that it would offer no fundamental difficulty.

If the raising of the back pressure of the turbine noticeably affects the flow of air through the power plant and the consequent approach to the pumping limit of the compressor has a disadvantageous effect, it may be appropriate to install a blowoff valve on the combustion chamber so linked to the jet nozzle that, with a reduction of the jet-nozzle flow area, air or combustion gas, as the case may be, is vented.

V. MODELS FOR CONTROL OF TURBINE-PROPELLER

JET POWER PLANTS

Figure 6 schematically shows an example of the design of controls for turbine-propeller jet power plants. The arrangements for the setting and the limitation of the fuel quantity and for the regulation of the propeller-blade setting, which may be in the same form as for the jet engine¹⁴ (in which the jet-nozzle flow area is regulated instead of the propeller-blade setting) are shown in this figure by solid lines; the remaining arrangements by dashed lines. In practice, the arrangements shown by dashed lines (control of the jet-nozzle flow area and modification of the speed in correlation with the propeller blade setting) may presumably be partly or wholly eliminated in many cases.

The arrangement here is such that in the entire operating range, at altitude as well as at sea level, substantially the whole travel¹⁵ of the pilot's control lever is utilized. With the

¹⁴With the exception of the arrangements for braking the propeller and for effecting the feathered position of the propeller that do not exist in the jet engine and are not treated here.

¹⁵Used at the suggestion of the Controls Development Subcommittee of the Donau Works of the Kienzle Apparatus Co. in place of the originally designed correlation of fuel quantity with pilot's control-lever travel.

exception of idling operation and of the perhaps almost unnecessary modification of the speed in accordance with the propeller-blade setting, each position of the pilot's control lever *a* is, in this system, correlated with a certain speed that is selected by way of the cam *b* and the lever *c* through shifting of the rod *d* and regulated by the propeller regulator *e* in the usual manner by changing the setting of the propeller blades.

The cam surface *f* is also linked to the pilot's control lever *a*; it rotates in accordance with the position of the lever and is shifted axially in accordance with the temperature ahead of the compressor T_1 . The turning of the lever *g*, which rests on the cam surface *f*, corresponds to the value of B/p_1 , which - as previously shown is required - is function of n and T_1 because of the correlation between speed and the position of pilot's control lever. The lever *g* presses upon the roller *h*, which is shifted vertically by the pressure capsule¹⁶ *i* as a function of p_1 in such a manner that its vertical distance from the fulcrum of the lever *g* is approximately¹⁷ proportional to the pressure p_1 . The horizontal shifting of the roller *h*, which is transmitted by way of the plate *k* to the rod *l*, is therefore proportional to the fuel quantity *B*.

As described in an earlier report¹⁸, the setting of the fuel quantity rate is accomplished, in effect, by alteration of the flow area of the control valve *m* built into the fuel supply line. By means of the diaphragm *n* upon which the pressure difference across the control valve *m* operates, the overflow valve *o*, which allows the excess fuel pumped to drain off, is so actuated that the pressure difference across the control valve *m* remains constant with the result that the fuel quantity supplied to the injection nozzles is proportional to the effective flow area of the control valve.

¹⁶The servo-amplifiers that might be necessary at certain points are omitted for the sake of simplicity because they are unnecessary to a basic understanding of the manner of operation.

¹⁷Small errors are introduced, for example, by the variable back pressure of the turbine and by the variation of combustion-chamber efficiency with p_1 .

¹⁸The arrangement shown in figure 6 for the setting and limitation of the fuel quantity corresponds substantially to that in figure 8, of reference 2.

If an injection pump on the order of the Bosch pump is to be used, the rod l should be linked to the pump's regulator lever. The fact that in this case the fuel quantity per revolution, and not as previously the fuel quantity per unit time, is selected can be essentially accounted for by merely altering the form of the regulating surfaces f and p retaining the same construction of the regulating system.

The cam surface p , which is rotated in accordance with the speed¹⁹ existing at the moment and shifted axially in accordance with the temperature ahead of the turbine, serves in the limitation of the fuel quantity when the maximum permissible gas temperature ahead of the turbine is reached and when the pumping limit of the compressor is approached. In the arrangement shown in figure 6, the rotation of the lever q corresponds to the maximum permissible value of B/p_3 at each moment. The roller r , which rests against the lever q , is linked to the pressure capsule s , which responds to the pressure p_3 . The vertical distance of the roller r from the fulcrum of the lever q is approximately proportional to the pressure p_3 ; its horizontal position corresponds to the maximum permissible value of B . If the pilot's control lever is so actuated as to select a greater fuel quantity, the plate t mounted on the rod l is brought up against the roller r ; this action limits the travel of the rod l and therefore the fuel quantity to the maximum permissible value.

If it should become necessary to allow for the influence of the back pressure behind the turbine p_4 upon the quantity of gas doing work, instead of the simple pressure capsule s , a pressure capsule and a capsule responding to the pressure difference $p_3 - p_4$ arranged in tandem may be used.²⁰

The fuel quantity set by the cam surface f is to be so adjusted that at partial load it always lies below the maximum

¹⁹The actual speed, which is to be used here, may temporarily differ considerably from the selected propeller speed in sudden changes of power.

²⁰As a further improvement, the fact that the influence of the back pressure decreases at higher values of the pressure ratio p_3/p_4 may also be accounted for by means of a correction capsule responding to the pressure p_4 which, coming into contact with the capsule responding to the pressure difference $p_3 - p_4$ at a specified value of the pressure ratio p_3/p_4 , operates at higher values of this ratio to oppose the action of the second capsule.

permissible quantity. Hence the limitation of the fuel quantity by the cam surface p will take effect only at full load and during acceleration. In this connection, it appears appropriate to use the cam surface p for the exact determination of the fuel quantity at full load. The exact determination of the maximum fuel quantity during acceleration is important because it assures the greatest acceleration that is possible without endangering the power plant.²¹

Because for the maximum fuel quantity the quotient B/p_1 may also be represented as a function of n and T_1 , the pressure capsule s may be eliminated and the cam surface p , which then, of course, would have a substantially different shape, may be allowed to actuate the lever g (fig. 6(a)). The advantage of this arrangement lies in its simplicity; the advantage of the previously described arrangement (fig. 6) lies in the relatively small influence of n and T_1 , therefore a rather low accuracy suffices in the response to these values and the cam surface p assumes a simpler shape. Furthermore, changes in the compressor-characteristics diagram have a less marked effect. Conversely, with variations of the turbine-nozzle flow area and with regard to the influence of the turbine back pressure, the arrangement in figure 6 would in principle be more advantageous, the more so if an injection pump on the order of the Bosch pumps is used because of the smaller influence of the speed.

The assumption may be made that with the arrangements described and without additional apparatus, a minimum limit for the fuel quantity can be effectuated. However, exact evidence on this point is unavailable.

If with regard to the pumping limit of the compressor at full power a limitation of the speed at a certain value of $n/\sqrt{T_1}$ is more advantageous than a limitation of the fuel quantity, this limitation may be accomplished by means of a stop lug u that is shifted in accordance with T_1 and, at low values of T_1 , limits the speed to values below the maximum speed.

The scheme of regulation so far described may also be used in unaltered form for the control of jet engines, the only exception being that the selected speed is established by alteration of the jet-nozzle flow area instead of by alteration of the propeller pitch. For the turbine-propeller jet power plant the devices to be subsequently described may be added.

²¹It is possible that during acceleration, that is, at speeds below the maximum speed, a somewhat higher gas temperature may be permissible than in steady operation.

If in reducing power from full power it is desired to have at high flight speeds a sharper reduction of the speed than at low flight speeds, the left end of the lever c is no longer fixed to the frame but is shifted vertically by the cam disk v in accordance with a function of the propeller-blade setting. The position reached by the rod d corresponds as previously to the speed to be established. The shapes of the cam disks v and b can be so correlated that in horizontal flight the desired dependence of the speed on the position of the pilot's control lever is secured. In climbing flight, the maximum speed is already reached at less than full power. By means of the stop lug w , against which, in this arrangement, the rod d comes to rest, the speed is held constant as the power output constantly increases.

If an automatic control of the jet-nozzle flow area as a function of $(p_3 - p_0)/(p_1 - p_0)$ is desired, this pressure ratio may be accounted for by the usual systems. In view of the low accuracy that will suffice here, however, a simpler arrangement will be obtained if, for example, a piston α upon which the pressure difference $p_3 - p_0$ operates is installed in opposition to a diaphragm β , having a variable effective area, upon which the pressure difference $p_1 - p_0$ operates. In order to obtain the variation of the effective area of the diaphragm, there are mounted movably on the rod γ , which carries the piston α and the diaphragm β , a series of concentric sleeves δ, ϵ . In the region of higher values of the pressure ratio $(p_3 - p_0)/(p_1 - p_0)$, these sleeves transmit to the rod γ the force exerted upon them by the diaphragm β , whereas with decreasing pressure ratio the sleeves come to rest, each in turn, against the housing ξ . As the effective area of the diaphragm to which the force exerted upon the rod γ corresponds, there then remains only the area within the sleeve that is in contact. The rod γ is thus shifted in steps as the pressure ratio changes and always at the same pressure ratios, independently of the absolute pressures. The adjustment of the jet nozzle takes place as a function of the rotation of the lever η . If the two end positions will serve all purposes, the alteration of the effective area of the diaphragm is, of course, unnecessary.

If adjustment of the jet nozzle to prevent the overstepping of a certain gear loading is necessary, this control of the jet nozzle can be effected, for example, as a function of the movement of the rod l by means of the lever θ and the cam disk ι , which when a certain fuel quantity is exceeded rotates the lever η to the left.

VI. APPENDIX. DERIVATION OF EQUATION FOR MOST ADVANTAGEOUS DIVISION OF POWER OUTPUT BETWEEN TURBINE AND JET NOZZLE

(SYMBOLS AS GIVEN ON PP. 4 AND 5.)

If computations are based, in the customary manner, upon the adiabatic work of expansion relatively complicated equations, which are not easy to comprehend, are obtained because of the necessity of accounting for the recoverable heat of friction. For the purposes of this report, it is therefore appropriate to base the computations upon the polytropic curve, the exponent of which corresponds to a mean efficiency of the turbine.

The relation between the polytropic and the adiabatic curves for a point on the expansion curve is, of course, obtained from the equation

$$\frac{n_G - 1}{n_G} = \eta^*_{t-pol} \frac{\kappa_G - 1}{\kappa_G}$$

where n_G is the exponent of the polytropic and κ_G of the adiabatic curve. The polytropic work of expansion L_{pol} per kilogram of combustion gas at the pressure ratio p_I/p_{II} may be computed from the corresponding adiabatic work of expansion L_{ad} by means of the equation

$$L_{pol} = L_{ad} \frac{1}{\eta^*_{t-pol}} \frac{1 - \left(\frac{p_{II}}{p_I}\right)^{\eta^*_{t-pol} \frac{\kappa_G - 1}{\kappa_G}}}{1 - \left(\frac{p_{II}}{p_I}\right)^{\frac{\kappa_G - 1}{\kappa_G}}}$$

using a mean value for κ_G . A mean value of the turbine efficiency η^*_{t-pol} will be used for determining all polytropic curves to be used in connection with the following relations.

If $L_{\text{total-pol}}$ denotes the total polytropic work of expansion between p_3 and p_0 , $L_{\text{t-pol}}^*$ the polytropic work of expansion in the turbine (computed on the total pressures ahead of and behind the turbine), and $L_{\text{d-pol}}$ the polytropic work of expansion in the jet nozzle (computed on the total pressure behind the turbine and p_0), the following equation applies exactly for constant $\eta_{\text{t-pol}}^*$ and within the limits in question here it applies for variable $\eta_{\text{t-pol}}^*$ in close approximation:

$$L_{\text{total-pol}} = L_{\text{t-pol}}^* + L_{\text{d-pol}}$$

In this equation, the cooling-air requirements of the turbine have been disregarded; the power cost of the cooling can be allowed for in the turbine efficiency value.

The jet velocity w_5 is found from

$$w_5 = \varphi_d \sqrt{2g L_{\text{d-pol}}} = \varphi_d \sqrt{2g(L_{\text{total-pol}} - L_{\text{t-pol}}^*)}$$

(g , acceleration of gravity) in connection with which the difference between the velocity coefficients φ_d as computed on polytropic and on adiabatic expansion is to be disregarded. The jet thrust S_s per kilogram of combustion gas per second that is imparted to the power plant by the flowing gas is then as follows where m denotes the fuel-air-mixture ratio:

$$S_s = \frac{w_5}{g} - \frac{w_0}{(1+m)g} = \frac{\varphi_d}{g} \sqrt{2g(L_{\text{total-pol}} - L_{\text{t-pol}}^*)} - \frac{w_0}{(1+m)g}$$

The work $L_{\text{p-w}}$ transmitted to the propeller shaft per kilogram of combustion gas is as follows where L_l' is the compressor work per kilogram of combustion gas:

$$L_{\text{p-w}} = L_{\text{t}} - L_l' = L_{\text{t-pol}}^* \eta_{\text{t-pol}}^* - L_l'$$

From the corresponding propulsive work $L_{\text{p-v}}$ of the propeller is computed the propeller thrust S_p per kilogram of combustion gas per second as follows:

$$S_p = \frac{L_{p-v}}{w_o}$$

From S_s and S_p is obtained the total thrust

$$S = S_s + S_p$$

With a change in the division of power output, the operating conditions remaining the same otherwise (that is, p_2/p_1 , T_o , p_o , w_o , T_3 , n , and λ being constant),²² the total thrust S and also the specific fuel consumption reaches its best value when

$$\frac{d S}{d L^*_{t-pol}} = \frac{d S_s}{d L^*_{t-pol}} + \frac{d S_p}{d L^*_{t-pol}} = 0$$

that is,

$$-\frac{\varphi_d}{2g} \sqrt{2g} \frac{1}{\sqrt{L_{total-pol} - L^*_{t-pol}}} + \frac{1}{w_o} \frac{d L_{p-v}}{d L^*_{t-pol}} = 0$$

By insertion of the equation for w_5 and from the following equation

$$\frac{d L_{p-v}}{d L^*_{t-pol}} = \frac{d L_{p-v}}{d L_{p-w}} \frac{d L_{p-w}}{d L^*_{t-pol}} = \frac{d L_{p-v}}{d L_{p-w}} \frac{d L_t}{d L^*_{t-pol}}$$

is obtained

$$-\frac{\varphi_d^2}{w_5} + \frac{1}{w_o} \frac{d L_{p-v}}{d L_{p-w}} \frac{d L_t}{d L^*_{t-pol}} = 0$$

and from this equation the jet velocity corresponding to the most advantageous division of power

²²If the critical velocity is not reached in the turbine nozzles, the constant pressure ratio in the compressor will actually correspond to small deviations of the speed (and hence also of the advance ratio λ), which, however, will be disregarded in the following treatment because they are not of any great importance for the final result.

$$w_{5opt} = \frac{\varphi_d^2}{\frac{d L_{p-v}}{d L_{p-w}} \frac{d L_t}{d L^*_{t-pol}}} w_o$$

Therefore

$$\begin{aligned} \frac{d L_{p-v}}{d L_{p-w}} &= \frac{d N_{p-v}}{d N_{p-w}} = \frac{d (w_o S_p)}{d N_{p-w}} = \frac{w_o dk_s}{u_p dk_l} = \lambda \frac{dk_s}{dk_l} \\ &= \frac{d (\eta_p L_{p-w})}{d L_{p-w}} = \eta_p + L_{p-w} \frac{d \eta_p}{d L_{p-w}} \\ &= \eta_p + \frac{d \eta_p}{d (\ln L_{p-w})} = \eta_p + \frac{d \eta_p}{d (\ln N_{p-w})} = \eta_p + \frac{d \eta_p}{d (\ln k_l)} \\ &= \eta_{\delta p} \end{aligned}$$

by introduction of the "differential efficiency" $\eta_{\delta p}$ as a new characteristic value.

By analogy

$$\begin{aligned} \frac{d L_t}{d L^*_{t-pol}} &= \frac{d (\eta^*_{t-pol} L^*_{t-pol})}{d L^*_{t-pol}} = \eta^*_{t-pol} + L^*_{t-pol} \frac{d \eta^*_{t-pol}}{d L^*_{t-pol}} \\ &= \eta^*_{t-pol} + \frac{d \eta^*_{t-pol}}{d (\ln L^*_{t-pol})} = \eta^*_{\delta t-pol} \end{aligned}$$

with $\eta^*_{\delta t-pol}$ as a new characteristic value.

With these new characteristic values

$$w_{5opt} = \frac{\varphi_d^2}{\eta_{\delta p} \eta^*_{\delta t-pol}} w_o$$

For very low flight speeds, especially for a speed of zero, another form of this relation is more advantageous. From

$$\frac{d N_{p-v}}{d N_{p-w}} = w_o \frac{d S_p}{d N_{p-w}} = \frac{w_o}{u_p} \frac{d k_s}{d k_l}$$

it follows that

$$w_{5opt} = \frac{\frac{\varphi_d^2}{d S_p} \eta^* \delta t - pol}{d N_{p-w}} = \frac{\frac{\varphi_d^2}{d k_s} \eta^* \delta t - pol}{d k_l} u_p$$

SUMMARY

Mathematical investigations of the behavior of turbine-propeller jet power plants under various operating conditions, computed on the assumption of constant efficiencies of the component units, have shown that the most advantageous correlation between the ratio of temperature ahead of the turbine to atmospheric temperature and the pressure ratio in the compressor is almost independent of the flight speed if the propeller efficiency is constant, and that a precise maintenance of the most advantageous correlation is unnecessary. Rather considerable variations may also be permitted from the jet-nozzle flow areas computed for the most advantageous division of the drop between turbine and jet nozzle, without incurring any important loss in power or in specific fuel consumption. Contrary to these generalized results, however, the numerical values computed cannot be applied without modification to an actual power plant because the assumption of constant efficiencies of the component units is in reality inaccurate.

It is possible by means of a simple representation to observe the course of the operating points in the propeller-characteristics diagram.

A relation is derived for the most advantageous jet velocity with variable efficiencies of the component units, which shows that this most advantageous jet velocity and the corresponding jet-nozzle flow area differ not inconsiderably when account is taken of the variable propeller efficiency from the values computed for constant

efficiencies. As a result of this, the differences in the most advantageous jet-nozzle flow areas under various operating conditions become substantially smaller than for constant efficiencies; therefore the prospect is that alteration of the jet-nozzle flow area may be eliminated over a large range of operating conditions. In general, it is only for full power at very low flight speeds, particularly in take-off, that a reduction of the jet-nozzle flow area would provide a substantial increase of the total thrust.

A simple possibility for designing the control consists in regulating the quotient of fuel quantity and pressure ahead of the compressor as a function of the speed and the temperature ahead of the compressor, or vice versa. In this connection the speed is established by alteration of the blade position of the variable-pitch propeller in the customary manner. To this arrangement are added the arrangements described in a previous report for the limitation of the fuel quantity. It may be necessary to provide a variation of the jet-nozzle flow area for high power at very low flight speeds and for the avoidance of an overstepping of the permissible gear loading.

A sample design sets forth an appropriate system for the control of the turbine-propeller jet power plant. With the exception of certain auxiliary devices required under certain circumstances for the turbine-propeller jet power plant, this system is one that can be used in unaltered form for the control of jet engines, in which case the speed is established by alteration of the jet-nozzle flow area instead of by alteration of the position of the propeller blades.

In further investigations the evidence now available will be supplemented and thereby a number of questions that could so far be treated only in broad outline will be further clarified.

Translation by Edward S. Shafer,
National Advisory Committee
for Aeronautics.

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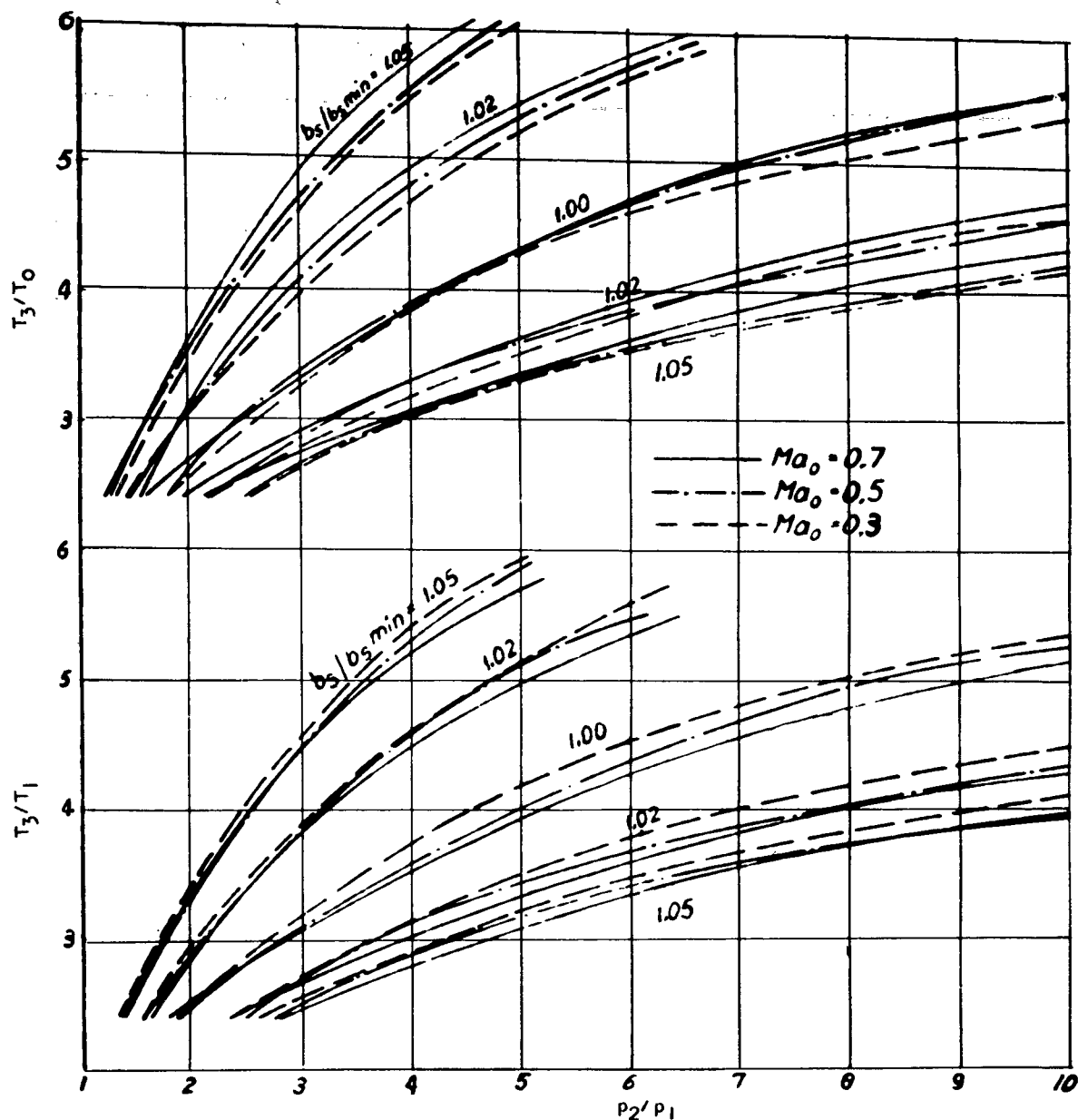


Figure 1. - Temperature ratios T_3/T_0 and T_3/T_1 as functions of pressure ratio p_2/p_1 for various values of b_s/b_{Smin} and various Mach numbers Ma_0 computed for turbine-propeller jet power plant with optimum division of power output and assuming constant efficiencies of component units ($\eta_{l-pol} = 0.85$; $\eta_{t-pol}^* = 0.75$; $\eta_p = 0.75$; $\eta_{st} = 0.90$; $\eta_b = 0.95$; $\mu_t = 0.94$; $\varphi_d = 0.96$; $p_3 = p_2$). For the influence of variable efficiency of propeller see section III.

Fig. 2

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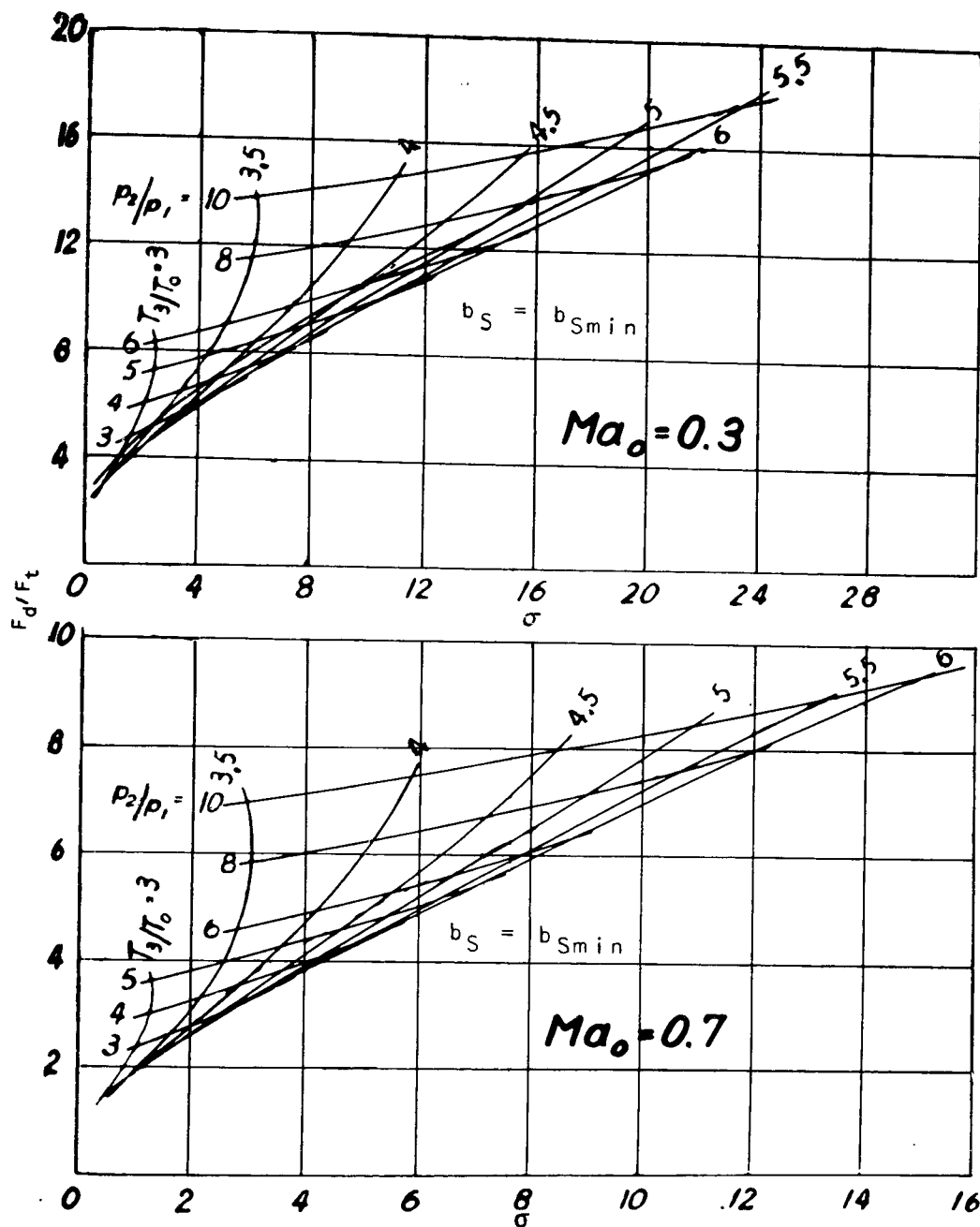


Figure 2. - Ratio of jet-nozzle flow area F_d to turbine-nozzle flow area F_t as function of thrust coefficient $\sigma = S/F_t p_0$ for Mach numbers $Ma_0 = 0.3$ and 0.7 and for various pressure ratios p_2/p_1 and temperature ratios T_3/T_0 computed for turbine-propeller jet power plant with optimum division of power output and assuming constant efficiencies of component units ($\eta_{pol} = 0.85$; $\eta_{t-pol}^* = 0.75$; $\eta_p = 0.75$; $\eta_{st} = 0.90$; $\eta_b = 0.95$; $\mu_t = 0.94$; $\varphi_d = 0.96$; $p_3 = p_2$).

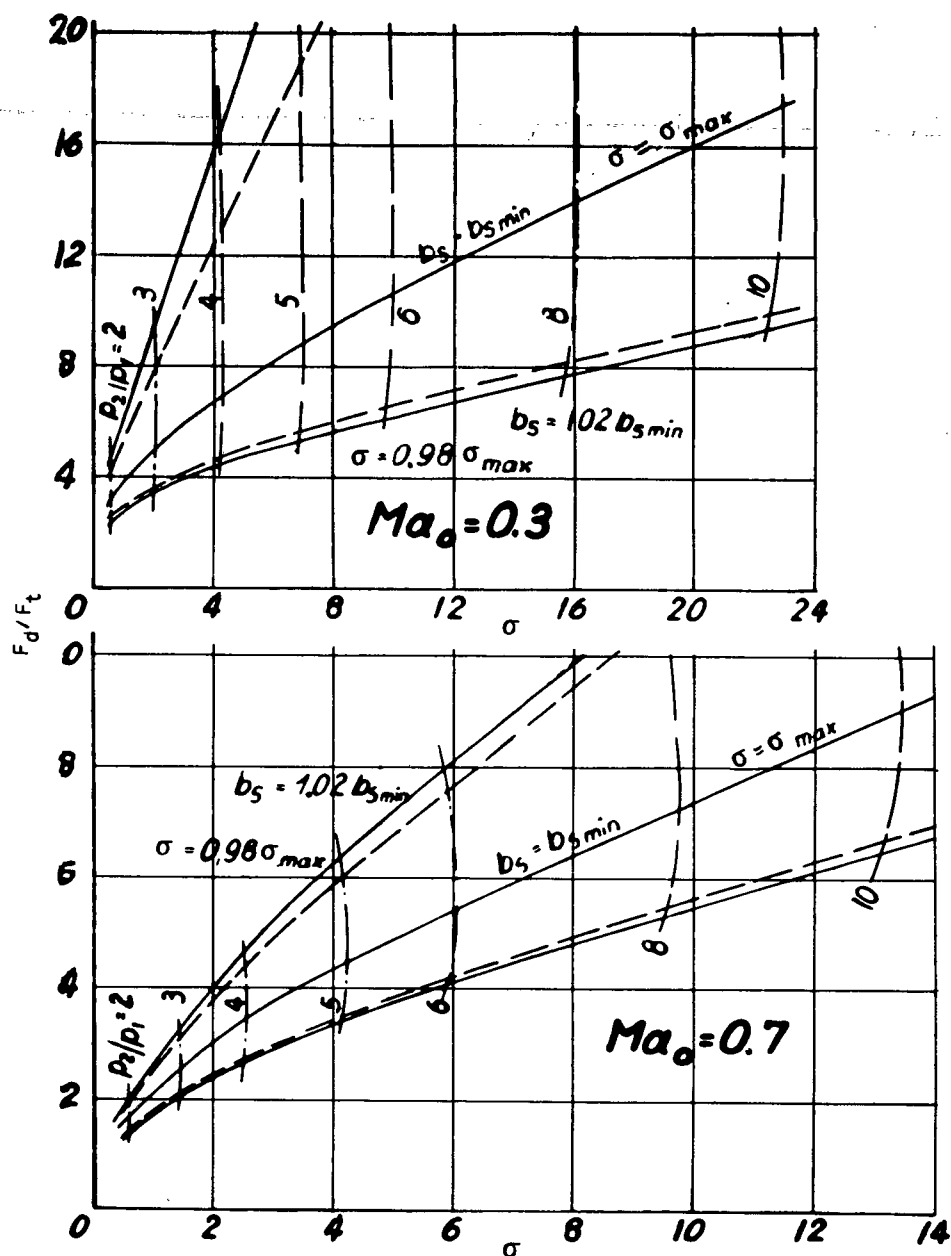


Figure 3. - Ratio of jet-nozzle flow area F_d to turbine-nozzle flow area F_t as function of thrust coefficient σ for two Mach numbers Ma_0 at that division of power output at which b_5 and σ each differ by 2 percent from optimum values b_{5min} and σ_{max} for optimum division of power; computed for turbine-propeller jet power plant with constant efficiencies of component units (values as for fig. 1) for correlation of T_3/T_1 with p_2/p_1 corresponding to $b_5/b_{5min} = 1$ as in figure 1.

Fig. 4

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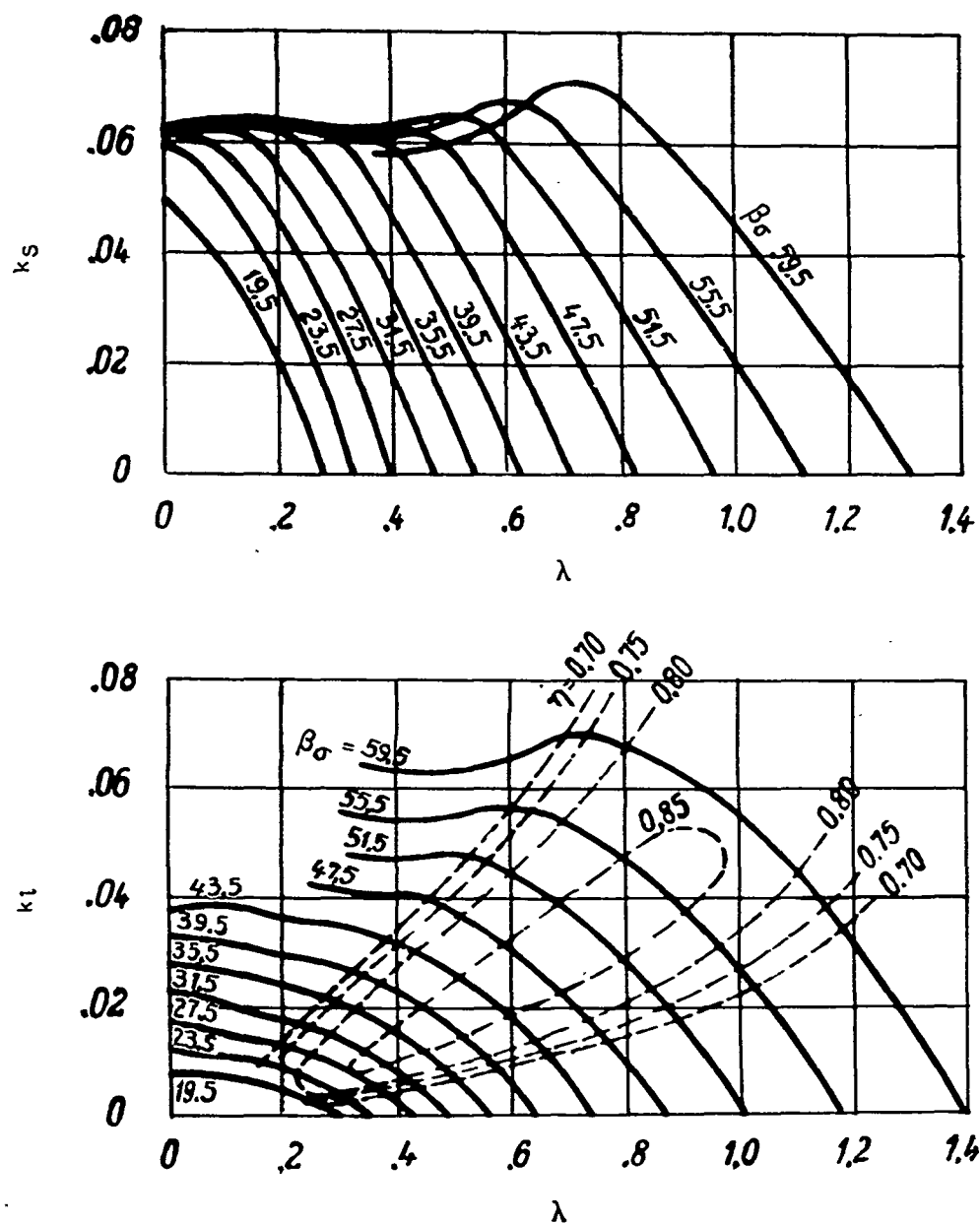


Figure 4. - Example of propeller-characteristics diagram (β_σ , blade angle of incidence).

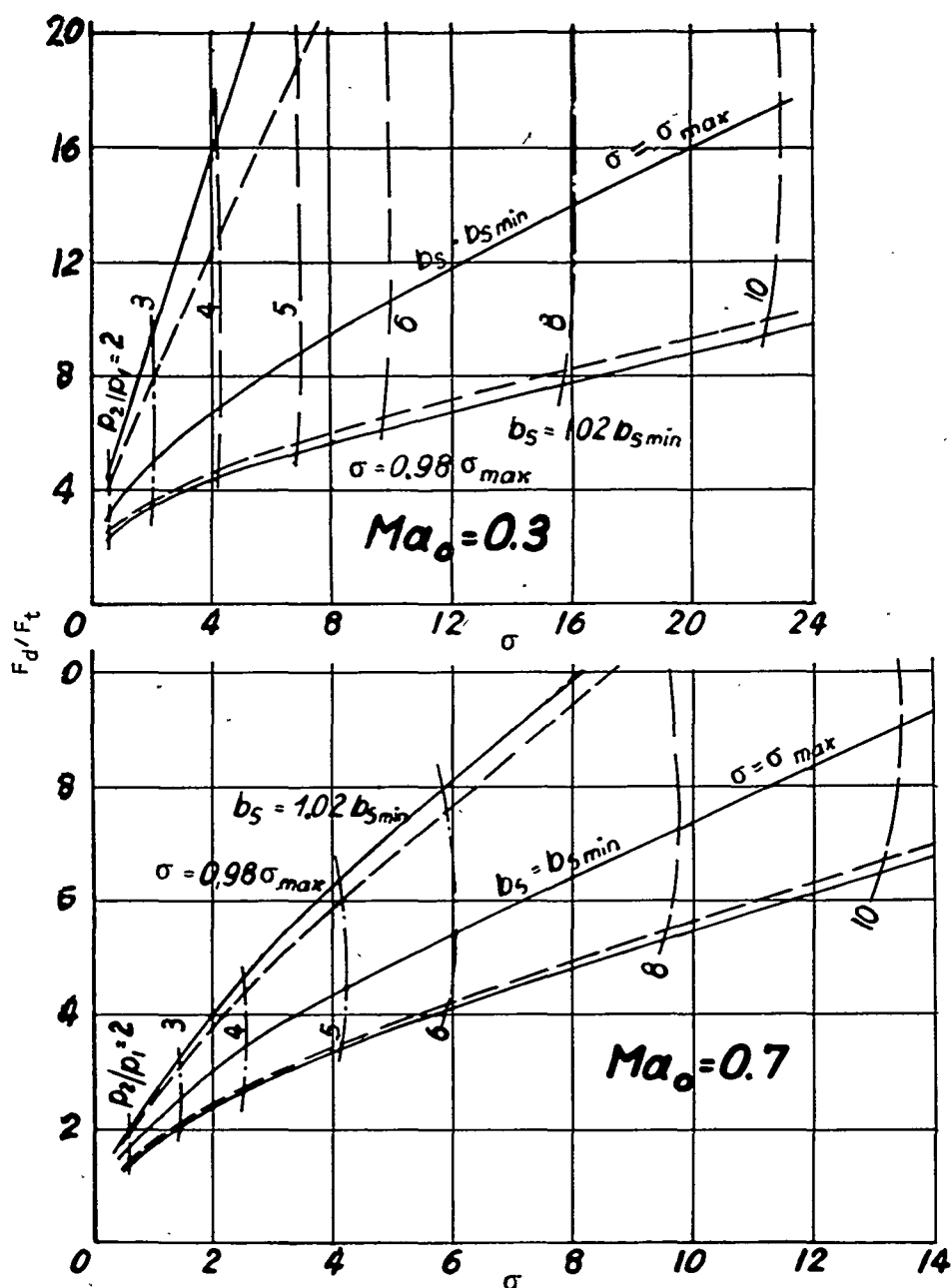


Figure 3. - Ratio of jet-nozzle flow area F_d to turbine-nozzle flow area F_t as function of thrust coefficient σ for two Mach numbers Ma_0 at that division of power output at which b_s and σ each differ by 2 percent from optimum values b_{smin} and σ_{max} for optimum division of power; computed for turbine-propeller jet power plant with constant efficiencies of component units (values as for fig. 1) for correlation of T_3/T_1 with p_2/p_1 corresponding to $b_s/b_{smin} = 1$ as in figure 1.

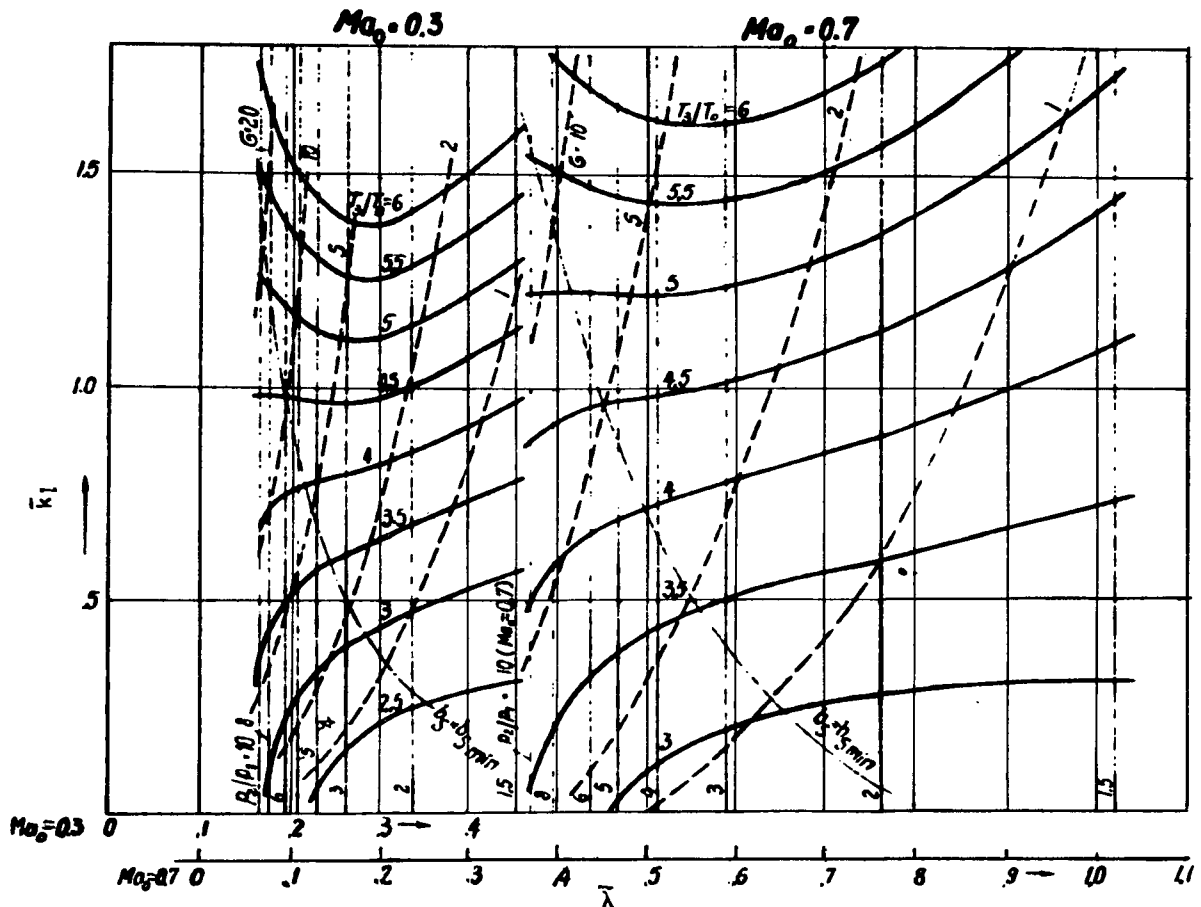


Figure 5. - Characteristic value \bar{k}_l as function of $\bar{\lambda}$ (see section III) for Mach numbers $Ma_0 = 0.3$ and 0.7 , various pressure ratios p_2/p_1 , and temperature ratios T_3/T_0 computed for a turbine-propeller jet power plant with optimum division of power output and assuming constant efficiencies of component units. ($\eta_{l-pol} = 0.85$; $\eta_{t-pol}^* = 0.75$; $\eta_p = 0.75$; $\eta_{st} = 0.90$; $\eta_b = 0.95$; $\mu_t = 0.94$; $\varphi_d = 0.96$; $p_3 = p_2$).

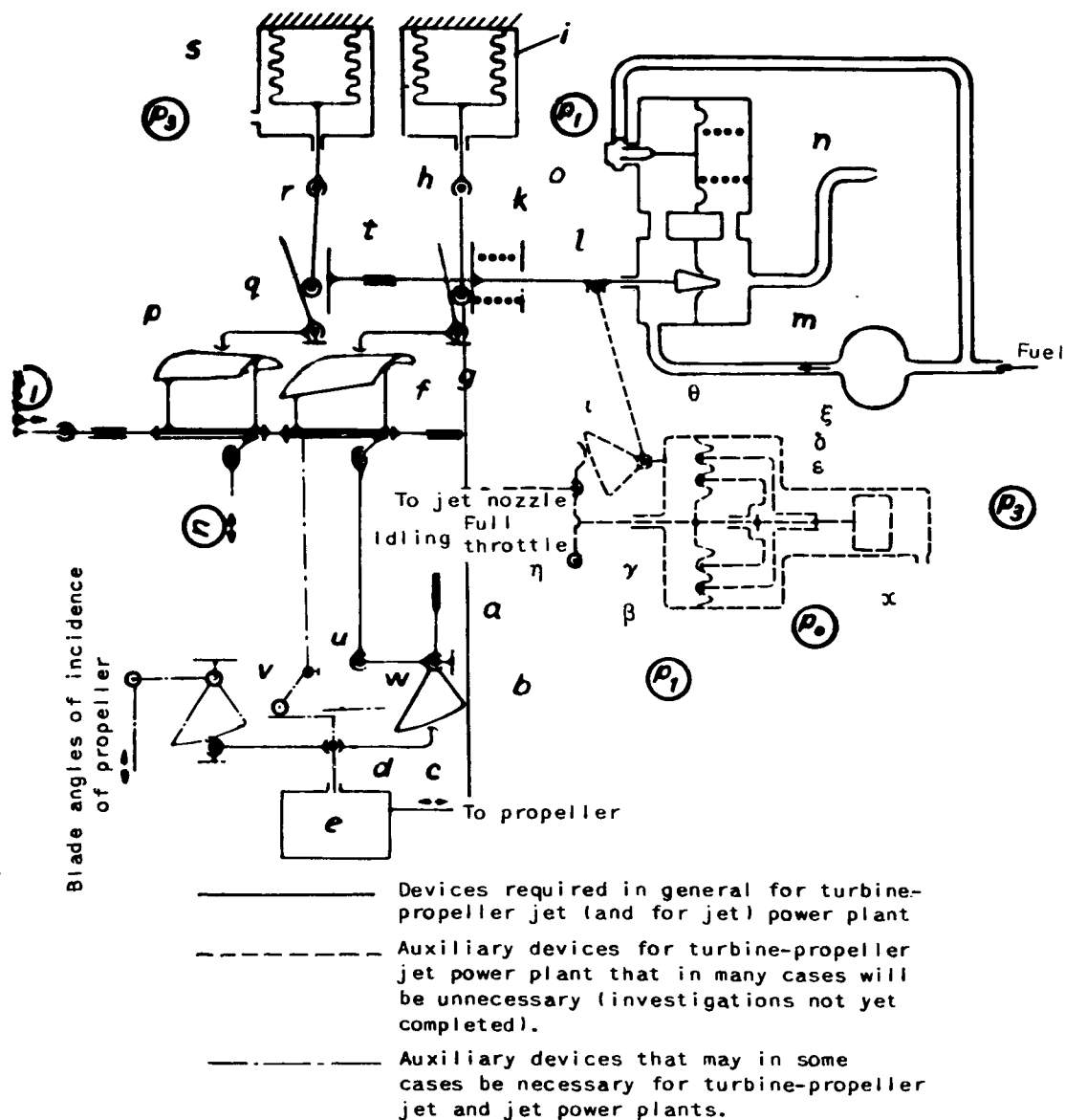


Figure 6. - Diagram of model for controls of turbine-propeller jet power plant.

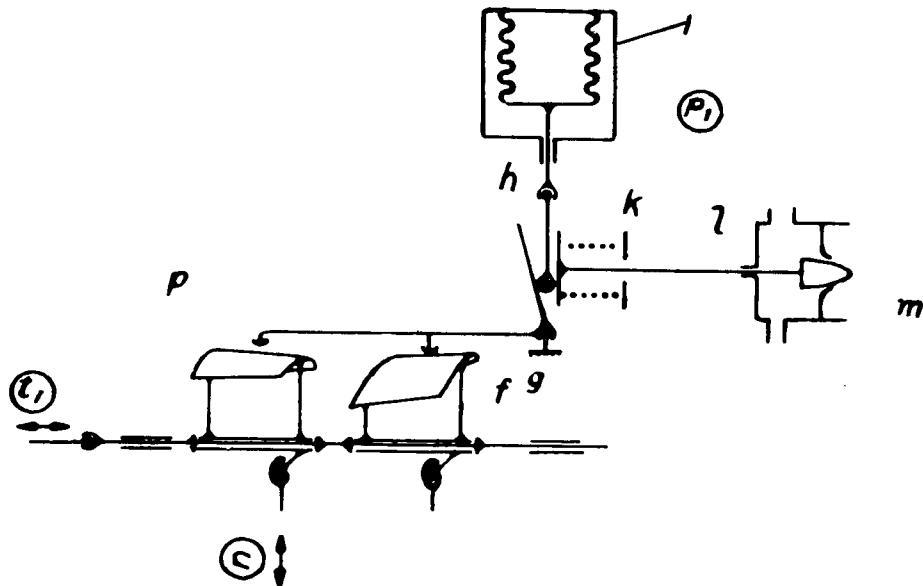


Figure 6(a). - Another possible arrangement for limitation of fuel quantity.

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